Sampling coarse woody debris for multiple attributes in extensive resource inventories

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Abstract

Information on the amount, distribution, and characteristics of coarse woody debris (CWD) in forest ecosystems is in high demand by wildlife biologists, fire specialists, and ecologists. In its important role in wildlife habitat, fuel loading, forest productivity, and carbon sequestration, CWD is an indicator of forest health. Because of this, the USDA Forest Service Pacific Northwest Research Station's Forest Inventory and Analysis (FIA) program recognized the need to collect data on CWD in their extensive resource inventories. This paper describes a sampling method, measurement protocols, and estimation procedures to collect and compile data on CWD attributes within FIA's forest inventory. The line-intersect method was used to sample CWD inside the boundaries of the standard inventory field plot. Previously published equations were customized to allow for easy calculation of per-unit-area values, such as biomass and carbon per hectare, log density per hectare, or volume per hectare, for each plot. These estimates are associated with all other information recorded or calculated for an inventory plot. This allows for indepth analysis of CWD data in relation to stand level characteristics. The data on CWD can be used to address current, relevant issues such as criteria no. 5 outlined in the 1994 Montreal process and the 1995 Santiago declaration. This criteria assesses the contribution of forests to the global carbon cycle by measuring such indicators as CWD, live plant biomass, and soil carbon. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Coarse woody debris; Down wood; Dead wood; Logging residue; Line-intersect sampling; Line transects; Resource inventory; Criteria and indicators

1. Introduction

Coarse woody debris (CWD) is present in most forest ecosystems; it provides living spaces for a host of organisms and serves as long-term storage sites for moisture, nutrients, and energy (Harmon et al., 1986). Also known as down logs, dead wood, down wood, and logging residue, CWD consists of fallen trees, large dead branches, and large fragments of wood found on or near the forest floor.

The ecological benefits of CWD are extensive. Bacteria and fungi establish quickly in moist, carbon-rich logs and are key to converting large masses of organic matter into inorganic remnants (Whittaker, 1975). As logs decay, they serve as shelter and food for a variety of invertebrates (Edmonds and Eglitis, 1989). Various shapes and sizes of CWD provide important habitat for many wildlife species (Bartels et al., 1985; Bull et al., 1997). Fallen trees function as germination sites for some shrub and tree species, which enhances plant establishment and survival in a competitive environment. CWD contributes to fuel loading in a forest and to total carbon storage within an ecosystem.

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Although these benefits are widely recognized, little is known about the character, extent, and distribution of CWD across the landscape. To expand the knowledge on CWD and describe the current status of this resource, the Forest Inventory and Analysis (FIA) program of the Pacific Northwest Research Station (PNW) in Portland, Oregon, integrated the sampling of CWD with their extensive resource inventories in California, Oregon, and Washington. In the mid-1980s, when CWD was being considered as a permanent addition to the FIA inventory, sampling techniques were evaluated to see how easily it could be incorporated into the existing field plot layout. Analysts in the FIA program adopted line-intersect sampling (LIS) because this technique had been successfully applied in a forestry context for many years to estimate logging residue and fuel loading in managed forests (Warren and Olsen, 1964; Van Wagner, 1968; Bailey, 1970; Howard and Ward, 1972; Brown, 1974; Warren, 1990; Larson, 1992). Because FIA was interested in the relationship between CWD and other ecosystem characteristics, an application of LIS was developed that integrated CWD attribute data with other stand and tree information collected in the inventory. The application includes linear transects overlaid on FIA's standard inventory field plot, specific tally procedures for a range of variables useful in ecological studies, and a series of per-unit-area equations to estimate CWD attributes at the plot level.

This paper describes the sampling and estimation procedures used by PNW's FIA program to assess various attributes of CWD collected in periodic resource inventories of west coast forests.

1.1. Line-intersect sampling applications in forestry

Warren and Olsen (1964) introduced the LIS technique to estimate the volume of logging residue in harvested forests of New Zealand. Circular or square plots had been used in the past but were costly and time-consuming to sample. Their new technique was based on the theory that a long rectangular plot with no width (i.e. a straight line) could be used to sample down logs and estimate volume across the landscape. A key discovery was that the volume of each log intersected by the transect line was related to the total volume in the sample area. A volume-per-unit-area formula was developed that required the number of

log intersections along the transect and an estimate of the average dimensions of down logs for the sample site. A separate field test was needed to assess these site-specific log dimensions.

A few years later, Van Wagner (1968) developed an alternative formula that required a diameter measurement from every log, but dispensed with the initial field test. This modification allowed log volume to change with individual log dimensions; however, his formula assumed that all logs were cylindrical and that the transect diameter represented the midpoint of the log. Van Wagner's formula has been used extensively to estimate volume of logging residue in the Northwest.

DeVries (1973) enhanced the versatility of Van Wagner's per-unit-area formula, by describing how *any* characteristic or attribute of the sample population could be estimated if the corresponding data were collected for each tally log. Rather than focus on volume or biomass, DeVries generalized the equation to allow substitution of any measured attribute into the formula. The availability of this equation form is one reason why LIS is useful for a wide range of disciplines.

DeVries' formula estimates a per-unit-area value for any attribute of interest, as follows:

$$\text{attribute per-unit-area} = \frac{\pi}{2L} \sum \frac{x}{l_i} \tag{1}$$

where L is the total length of the transect line in the area being sampled, x is a value for the attribute of interest for an individual piece of CWD, l_i is the length of the individual piece, used to weight the piece attribute.

In this equation, the weighted attribute is summed across all transects in the sample unit before conversion to a per-unit-area estimate. In the case of an FIA field plot, data from all transects on all subplots in one forest condition on one plot (the sample unit) would be summed and then converted to a per-acre estimate for the individual plot or condition. DeVries' generalization of the formula to allow calculation of any attribute, made the equation easy to understand and apply. For example, attributes such as number of logs, percentage of cover, linear feet of down wood, carbon, number of insects, or number of wildlife dens per log can be estimated on a per-unit-area basis with a single equation. Even the more common volume and biomass calculations can be improved because the user can choose as simple or as complex an equation for log volume as needed and substitute this

volume for the placeholder variable '*x*' in Eq. (1). This contrasts with Van Wagner's earlier equation that embedded a specific volume formula and log form into the equation, which left no flexibility to customize for a particular application.

The planar intersect method is an extension of LIS developed primarily to estimate the volume and biomass of small-sized fuel particles (<7.6 cm in diameter) within predefined diameter classes (Brown, 1971). Although Brown also described how the method could be used to develop estimates of larger fuels (CWD), some have suggested that the planar intersect method is the same as LIS because of the latter's implicit assumption that sampling occurs through a vertical plane along the transect (DeVries, 1973; Van Wagner, 1982). One difference introduced by Brown (1974) was the subdivision of the traditionally long sampling lines into multiple smaller transects on the sample unit. This helped to ensure that a more extensive area was sampled within plot boundaries; however, the total transect length (*L*) used in estimation equations remained as the total length of line (i.e. the sum of the lengths of all short transects) installed on the plot or condition. A handbook was developed that explains sampling procedures using the planar intersect method for all sizes of down wood (Brown, 1974).

Howard and Ward (1972) tested alternative configurations of sampling lines within harvested areas to estimate volume of logging residue. They observed that the amount of residue (down wood) was highly variable across a cutover area and that a small number of long lines did not adequately pick up this variation. They installed numerous shorter transects on a grid system inside a clear-cut and concluded that this provided more reliable estimates of residue volume.

The application presented here uses the multiple short-transect aspect of Brown (1974) and Howard and Ward (1972), some tally protocols described by Brown (1974), and the estimation equations described by DeVries (1973).

1.2. Sources of error with LIS

Three sources of error are recognized for the LIS method; these involve basic assumptions about log shape, log orientation relative to local topography, and elevation of the log relative to the ground surface (i.e.

horizontal versus vertical). First, many formulas assume log shape is cylindrical and rely on one diameter at the point of intersection to calculate volume. This simplification assumes that logs have no taper and that the point of intersection represents the midpoint of the log. In fact, logs have a wide range of shapes and sizes, and the point of intersection can occur anywhere along the log. Although Van Wagner (1968) reports that taper introduces little or no bias, both Bailey (1970) and Pickford and Hazard (1978) show that it adds considerably to the variation of volume estimates. Pickford and Hazard tested the volume of an artificial population of cone- and cylinder-shaped logs calculated with Van Wagner's formula. Because this formula assumes logs are cylinders, it is not surprising that the variation of conic volume was almost double that of the cylindrical volume. They suggest that additional measurements on the log, such as length and another diameter, would allow more accurate volume equations to be used and eliminate much of the variation between populations of different geometric shapes. The central section of a tree bole is generally shaped as a frustum of a paraboloid (Husch et al., 1972). Assuming that most down logs have this general shape, Smalian's formula (see Husch et al., 1972) is best suited to estimate cubic volume from small- and large-end diameters and length.

A second assumption is that pieces are randomly oriented throughout a sample area with a Poisson distribution. If a transect line crosses a cable-yarded harvested site that has log residue positioned primarily in one direction, then this assumption is violated and the sample is not random. Van Wagner (1968) called this "piece orientation bias" and suggests that the effect of this bias can be substantially reduced by running two or more transects out from a common point, at different angles (see also Bailey, 1970; Howard and Ward, 1972; DeVries, 1986; Hazard and Pickford, 1986). By sampling along transect lines laid in different directions, the number of logs that intersect the lines can be assumed to be unbiased and unrelated to their angle position on the slope.

The last bias relates to the assumption that all pieces lay horizontally on the ground. In a forest setting, some pieces may be propped up at an angle and elevated slightly off the ground. Van Wagner (1968) found, however, that the vertical angle of a piece can be quite large before a serious error will occur in the volume

estimate. Although Brown (1974) used the average secant of the angles of nonhorizontal pieces to correct for this bias, he applied the correction only to fine fuels (<7.6 cm in diameter) and set the correction factor to 1.0 for larger fuels. Apparently concern for vertical angle bias on larger pieces of CWD is generally ignored.

2. Methods

The PNW FIA program conducts extensive resource inventories in the forests of Alaska, California, Oregon, Washington, Hawaii, and the Pacific Islands. These inventories use a double sampling for stratification design to collect detailed measurements on many ecosystem attributes. Two sets of plot locations are selected via systematic sampling grids, which are superimposed on the entire region. Primary sample plots are evaluated by photo-interpreting points on aerial photos. The secondary sample consists of permanently established field plots where a variety of measurements are recorded for ecosystem components, including live and dead trees, understory vegetation, and CWD. Estimates of land area by forest type, live and dead tree volume, harvest volume, forest productivity, wildlife habitat potential, density of CWD, and aboveground biomass are examples of resource characteristics calculated from plot data.

In 1984, PNW FIA collected data on CWD from inventory plots in a few counties of western Oregon to test and refine sampling procedures. By 1990, collection of CWD data using the line-intersect method to sample down wood along linear transects was fully incorporated into the standard field plots of PNW's 10-year periodic forest inventories. These comprehensive resource inventories provide plot-level data on the amount, distribution, and characteristics of CWD that can be related to the detailed attribute data for other ecosystem components on the same plot.

The sampling methods described below pertain to procedures used in the periodic inventories conducted since 1990. Some of these methods have been modified slightly for the new annual inventory design being implemented by the national FIA program. These changes will be mentioned briefly at the end of Section 2.

2.1. Plot layout

Field plots in PNW FIA periodic inventories consist of a cluster of five subplots (Fig. 1). Linear transects are installed in forest conditions on all subplots in the inventory. To avoid piece orientation bias, three 17 m (56 ft) transects (slope-corrected, horizontal distance) are established at each subplot location. Each transect originates at the subplot center and extends out at 0, 135, and 225° (Fig. 1a). The length, azimuth, and number of transects have changed over time as techniques have evolved and as modifications were made to the PNW FIA inventory design.

Although plot layouts were altered in the past and likely will change to some extent in the future, the types of data collected and subsequent estimation procedures remain essentially unchanged.

All FIA subplot clusters are laid out in a fixed pattern regardless of the different conditions (forest, roads, grassland, etc.) that may exist on the plot. It, thus, would be possible for a transect to cross a condition boundary and sample land area classified differently from the subplot center. Only the transect segment that falls within a forest condition is sampled for CWD. All conditions are identified along the length of the transect. The point where the condition changes is marked, the length of the transect line within each condition is recorded, and each piece of CWD tallied is associated with a particular condition. Equations used to estimate CWD attributes require the total length of transect line within the specific condition being sampled. Often, there is only one condition on a plot, therefore, the total transect length is equal to the sum of the lengths of all individual transects installed on the five subplots. Multiple conditions effectively partition an FIA plot into multiple sample units for analysis.

2.2. Tally procedures

The PNW FIA inventory defines CWD as dead tree boles, large limbs, and other large wood pieces either lying on the ground or elevated off the ground up to 45°, but no longer supported by roots (i.e. dead trees hung up or leaning on other vegetation). CWD does not include live material, standing dead trees, stumps, dead foliage, separated bark, nonwoody pieces, roots, or the part of the bole below the root collar. In the periodic inventory design, a piece of CWD is measured

Inventory field plot

Subplot

Cluster of 5 subplots

Three 17 meter
transects per subplot

(a)

Cluster of 4 subplots
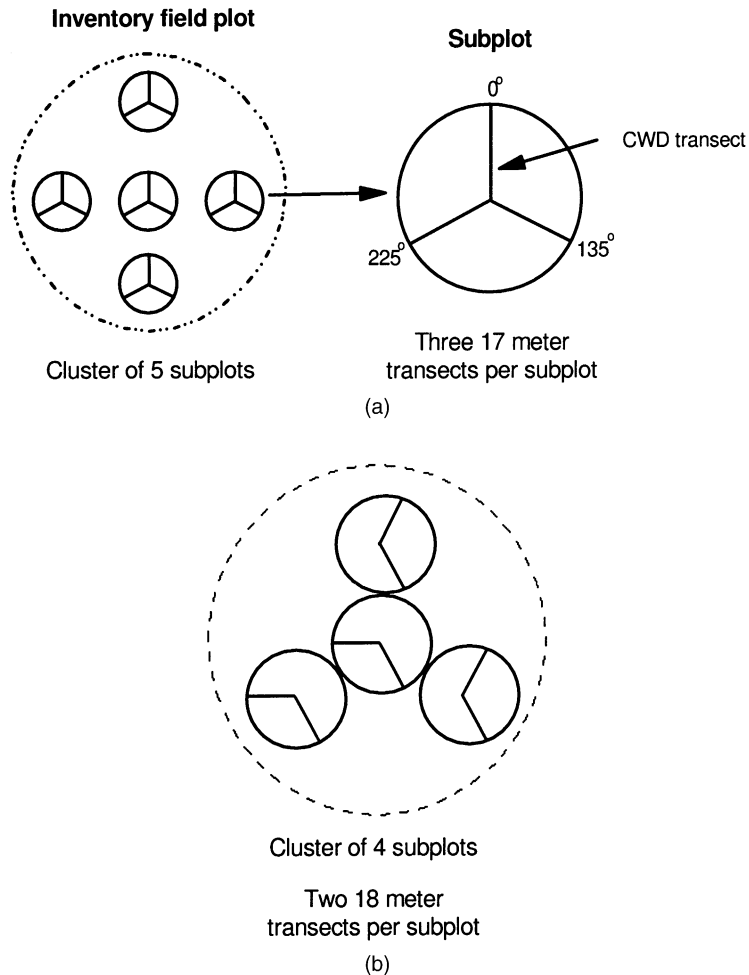
Two 18 meter
transects per subplot

(b)

Fig. 1. Example of FIA inventory field plots: (a) periodic inventory plot with three transects installed on each of five subplots; (b) national annual inventory plot with two transects installed on each of four subplots.

if it meets the following specifications (Fig. 2):

1. the central longitudinal axis of the piece intersects the transect;
2. the diameter at the point of intersection is at least 12.5 cm (5 in.);
3. the piece length is at least 1 m (3.3 ft);
4. the piece is not decayed to the point of having no structural integrity. Note that these specifications may change as inventory objectives change (for example, item 4 above might be modified to include heavily decayed pieces, if there is a need for this information).

Most CWD pieces that cross the line are a simple intersection of a fairly straight tree bole with the transect line. Other more unusual situations occur when CWD is less uniform in shape. When a tree is forked or has a very large branch attached to the main bole— and both segments intersect the transect—they are tallied as two separate pieces, if each meets the required minimum dimensions (Fig. 3). Forked trees are examined to identify one fork as the main bole by measuring both diameters at the fork location. The forked segment with the largest diameter is considered the main bole and the length is measured from the tip of the fork to the end of the log. The smaller segment
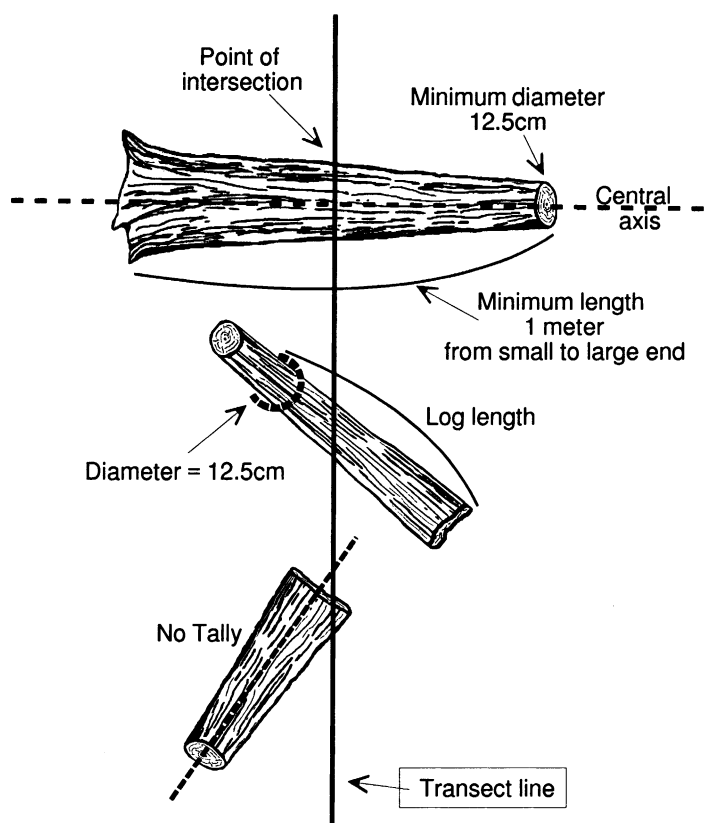
Fig. 2. Logs intersecting the transect line. Tally logs must cross the line through the central log axis. Minimum dimensions are shown for small-end diameter, point of intersection, and log length.

is recorded as a second piece with a length measured from the fork tip down to the point where the fork joined the main bole.

A piece is tallied twice if it intersects two different transects or if it is nonlinear and intersects the same transect in two locations (Fig. 4). Although this may appear to be double-sampling of CWD pieces, it conforms to the statistical theory behind LIS. For example, on one plot, an estimate of CWD volume may be high because a piece was tallied twice, but on another plot the estimate may be low because one or more CWD pieces were parallel to the transect and not tallied. Summaries or analyses for the entire inventory area will produce unbiased, statistically valid results.

When a transect crosses into a new condition, CWD pieces were tallied if they had the required dimensions and if both the midpoint along the length of the piece and the point of intersection were within

the same condition. Because it is rare to tally a piece where these points are in different conditions, FIA is considering a simpler rule that dispenses with the midpoint requirement: Every qualifying piece intersecting the transect in a forest condition would be tallied and the entire piece assigned to the condition class found at the point of intersection.

2.3. Measurements recorded on tally logs

Three diameters are estimated to the nearest centimeter: the small-end, large-end, and point of intersection. Diameters are measured by surrounding the log with a tape, but often this is not possible because the log is in contact with the ground. In this case, either the diameter is visually estimated by holding the tape above the log and perpendicular to the central axis, or an average diameter is calculated from
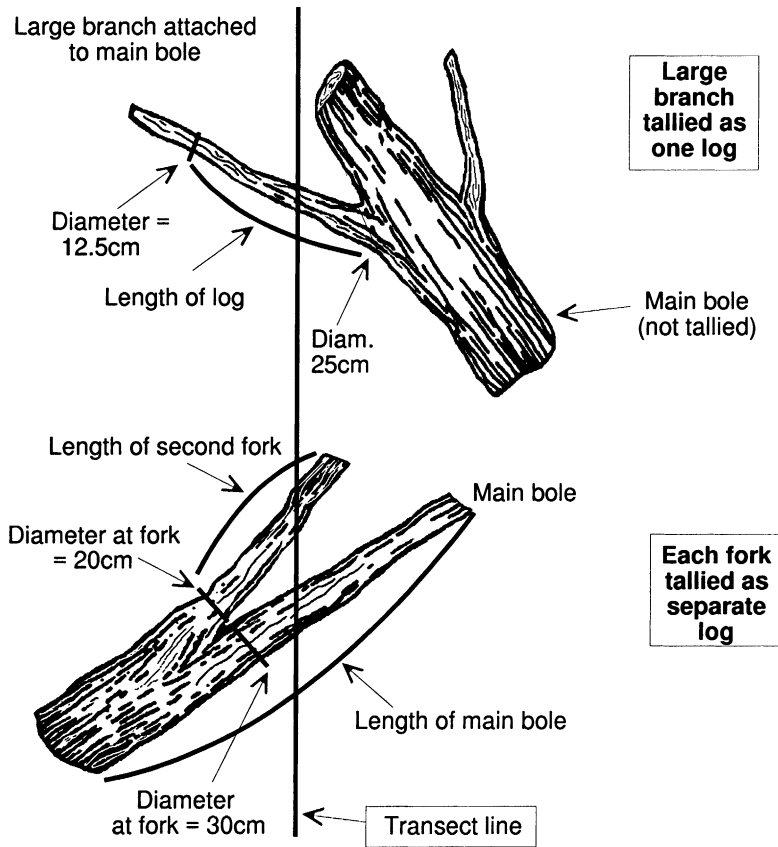
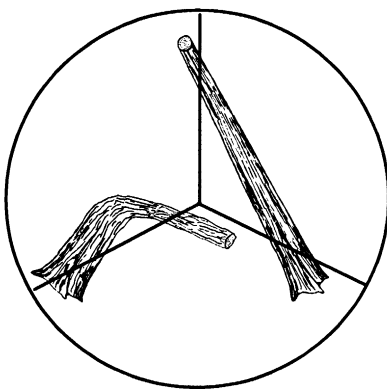Fig. 3. Forked or branched logs intersecting the transect line.

Fig. 4. CWD intersecting transect lines at two locations.

two measurements taken on the cross-sectional face of the log end. The minimum small-end diameter was set to 12.5 cm, therefore, all measurements end at this point. Small- and large-end diameters are needed to calculate an accurate volume and cover estimate for the log. Because volume is the starting point for estimating biomass, carbon, and other variables of keen interest to multiple clients and partners, FIA analysts decided to estimate volume with an equation that considers log taper and incorporates two diameters. In addition, large-end diameters provide a more meaningful description of the population of CWD pieces in terms of relative size. Down wood characterized by its large-end diameter is more easily related to stand size and structure information recorded on the plot. Discussions, summaries, and analyses based on diameter at the point of intersection are harder to interpret because this diameter can be located anywhere along the length of the piece, and thus, little information is provided about the actual size of CWD present.

Table 1
Classification of the stage of decay for coarse woody debris logs

Decay class[a]	Structural integrity	Wood texture	Wood color	Presence of invading roots	Condition of branches and twigs
1	Sound	Intact, no rot; conks on stem absent	Original color	Absent	If branches present, fine twigs still attached with tight bark
2	Heartwood sound; sapwood somewhat decayed	Mostly intact; sapwood partly soft and starting to decay. Wood cannot be pulled apart by hand	Original color	Absent	If branches present, many fine twigs gone; fine twigs still present have peeling bark
3	Heartwood sound; log supports its weight	Large, hard pieces sapwood can be pulled apart by hand	Red-brown or original color	Present in sapwood only	Large branch stubs will not pull out
4	Heartwood rotten; log does not support its weight, but shape is maintained	Soft, small, blocky pieces; metal pin can push apart heartwood	Red-brown or light brown	Present throughout log	Large branch stubs pull out easily
5	No structural integrity; no longer maintains shape	Soft, powdery when dry	Red-brown to dark brown	Present throughout log	Branch stubs and pitch pockets have rotted away

Sources: modified from Maser et al. (1979) and Sollins (1982).

[a] The decay class recorded for a log is the stage of decay that predominates along the length of the log.

The length of the CWD piece is measured to the nearest meter. If a log extends beyond the minimum small-end diameter, the length measurement ends where the diameter tapers to 12.5 cm (5 in.). Because heavily decomposed CWD (decay class 5) is excluded from this inventory, the length measurement ends at the point where decay class 5 begins.

The stage of decay is classified for each tally log, by using a five-class system (Table 1) described by Maser et al. (1979) and Sollins (1982). Decay classes attempt to identify the range of decomposition occurring in CWD throughout the forest, from recently fallen logs that consist of hard, solid wood to older logs that are soft and rotten. Each piece is assigned the decay class predominating along the length of the piece. Any CWD in an advanced stage of decay (class 5) is not sampled in the FIA periodic inventory because of difficulty in delineating the log on the ground to obtain measurements of diameter and length.

The species of each piece is determined by examining bark, heartwood, and branching pattern if intact. The presence of large hollow cavities is recorded to help estimate the amount of available logs suitable for wildlife cover. If a log has a cavity at least one-half meter long into the center of the log and the diameter

of the entrance hole is at least one-quarter of the end diameter, the log is coded as hollow.

The position of the log in relation to the predominant slope of the land is thought to influence the rate of decay and degree of use by wildlife (Bull et al., 1997). Logs positioned along slope contours are important in steep areas, where materials are likely to collect along the upslope side of the log. Pieces of CWD are examined to determine the orientation of the log on the slope and are classified into one of four possible positions (Fig. 5).

A copy of the detailed field instructions used by FIA inventory crews is available upon request.

2.4. Expected changes to field methods in the annual inventory design

A new, nationally consistent inventory design is being implemented for both FIA and Forest Health Monitoring (FHM) plots across the country on an annual basis. CWD will be sampled on all FHM plots and on PNW FIA plots in Oregon, Washington, and California in this new inventory. The new design consists of a cluster of four fixed-radius subplots, with two 18 m (58.9 ft) transects extending out from each subplot center (Fig. 1b). Expected differences in tally
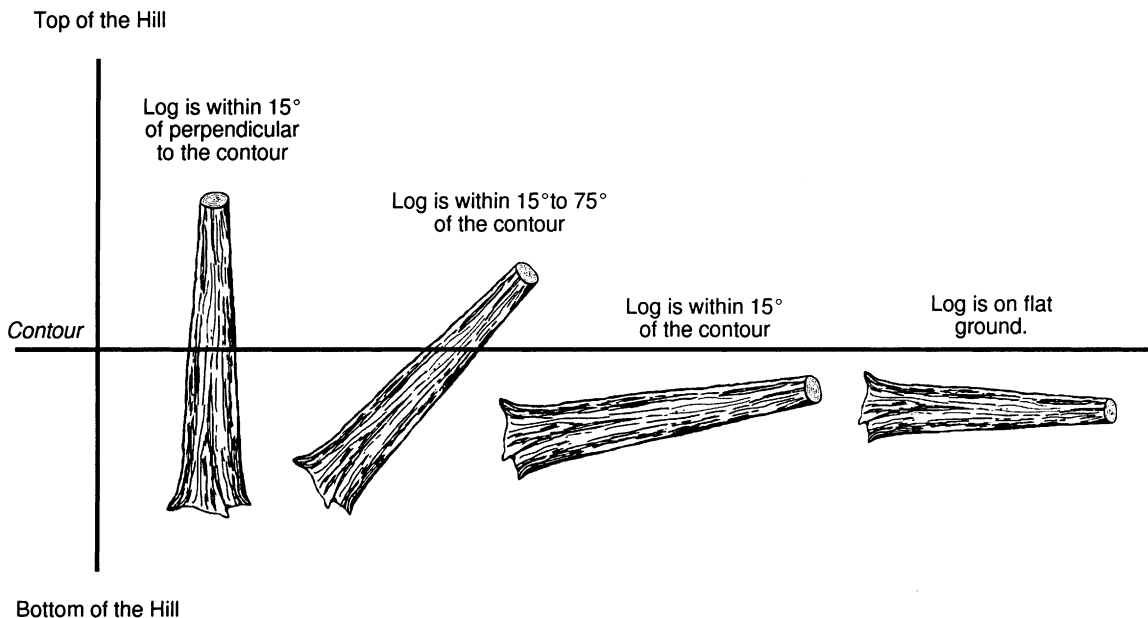

Fig. 5. Orientation of tally logs on a slope.

procedures are that the minimum small-end diameter will be reduced to 7.6 cm (3 in.); minimum piece length will be 0.9 m (3 ft); pieces in decay class 5 will be tallied; and standing dead trees leaning >45° from vertical and still supported by a root system (rare situation) will be tallied as CWD. Other variables being considered are the percentage of a log charred by fire and a history code indicating how the log fell to the ground (i.e. the result of harvest activity, firewood cutting, or natural causes).

3. Attribute estimation

An attribute of CWD can be any item or characteristic of the CWD population that a researcher or manager is interested in estimating on a per-acre or per-hectare basis. For example, FIA estimates and reports cubic volume, number of logs, linear feet, biomass, and carbon, all per hectare, from data collected on the transects. These estimates are calculated for individual pieces of CWD first, before being summed to the plot level or condition class level for analysis. Comparisons of population attributes can be made by analyzing the plot-level sums within categories, such as decay class, species groups, and diameter class, or by evaluating CWD totals for various categories based on non-CWD attributes (i.e. forest type, elevation, or successional stage).

The CWD sample population is defined by the same boundaries set-up for the FIA resource inventory. Because the primary sampling unit is the plot, the estimate of variance or standard error for CWD attributes is calculated at the plot (or condition class) level according to procedures valid for the FIA inventory design. Although the variance may be over-estimated to some degree, it is also valid to consider the sample of inventory plots as a simple random sample. A weighted mean and standard error can be estimated across conditions (portions of plots) using the proportion of the plot within the condition as the weight.

3.1. Total transect length

The total length of the transect line (L) for each plot is the sum of all individual transect lengths (horizontal distance) across all subplots on the plot (or, if multiple conditions exist, it is the sum of transect lengths within

one condition). In line-intersect sampling theory, L is considered to be one long sampling line on the plot (Hazard and Pickford, 1979).

3.2. Volume of individual pieces

A number of simple cubic volume equations for common log shapes such as a cylinder, paraboloid, or neiloid are shown by Husch et al. (1972); each require one, two, or three diameter measurements. The FIA program chose an equation that takes taper of the log into account, because an accurate estimate of volume was important when converting to other attributes such as biomass and carbon stores or when conducting an analysis of individual log characteristics. Smalian's volume formula (see Husch et al., 1972) was used, and requires log length and both small- and large-end diameters as shown:

$$\text{cubic volume of a log}: \quad V_{\text{ft}} = \frac{(\pi/8)(D_{\text{S}}^2 + D_{\text{L}}^2)l}{144} \tag{2}$$

where V_{ft} is volume in cubic feet, D_{S} the small-end diameter in inches, D_{L} the large-end diameter in inches, l the log length in feet.

To obtain volume in cubic meters, use centimeters for diameters, meters for length, and substitute the constant 10,000 for 144.

Huber's formula (see Husch et al., 1972) can be used to estimate volume when the diameter at the point of intersection is the only measurement available, which, for English units, translates to

$$V_{\text{ft}} = \frac{(\pi/4)D^2 l}{144} \tag{3}$$

This is the formula embedded in equations presented by Van Wagner (1968) and Brown (1971) and has been shown to provide unbiased estimates. The equation assumes a cylindrical shape, however, and that the diameter is measured at the midpoint of the log. Regardless of the equation used, the individual log volume is substituted for the attribute x in DeVries' equation (Eq. (1)) to estimate volume per-unit-area.

3.3. Per-unit-area estimates

All CWD attributes are estimated with DeVries' (1973) per-unit-area formula (Eq. (1)). For this appli-

Table 2

Equations to estimate per-unit-area values (after DeVries, 1973) for CWD attributes of individual pieces tallied with the line-intersect sampling method on resource inventory plots[a]

Attribute	Equation (for each piece)	Units for each equation variable[b]				
		L	V	l	D	f
Cubic feet per acre[c]	$(\pi/2L)(V_{ft}/l_i)f$	ft	ft^3	ft	in	43560 ft^2/acre
Cubic meters per hectare	$(\pi/2L)(V_m/l_i)f$	m	m^3	m	cm	10000 m^2/ha
Logs per acre	$(\pi/2L)(1/l_i)f$	ft	–	ft	–	43560 ft^2/acre
Logs per hectare	$(\pi/2L)(1/l_i)f$	m	–	m	–	10000 m^2/ha
Linear feet per acre	$l_i \times$ logs per acre	–	–	ft	–	–
Linear meters per hectare	$l_i \times$ logs per hectare	–	–	m	–	–
Percentage of cover	$0.25\pi(D_S + D_L)/L$	m	–	–	cm	–
Percentage of cover[d]	$0.5\pi D_i/L$	m	–	–	cm	–

[a] Results of these equations must be summed to the plot level before analysis.

[b] L: total length of the transect line on the plot; if multiple conditions exist, L is the total length within one condition (sum of horizontal distance across subplots), V_{ft}: volume in cubic feet of the individual piece, V_m: volume in cubic meters of the individual piece, l_i: length of the individual piece, D: diameter of the individual piece; D_i, D_S, D_L: point of intersection, small- and large-end diameters, respectively, f: a factor to convert the result to a per-acre or per-hectare value.

[c] Volume equations can be further simplified depending on the volume equation chosen for individual pieces, because piece length cancels out.

[d] This equation can be used when only the diameter at the point of intersection is available.

cation, the equations were customized for attributes commonly used in the analysis of FIA data and are presented in Table 2 as individual piece (log) equations (as opposed to plot-level equations). Although these equations usually are displayed in the literature in terms of the sample unit (plot) sum (see Eq. (1)), calculating estimates for each individual piece allows this information to be stored easily in a database along with the field-measured CWD data and other tree and plot attributes. Ultimately, this simplifies the summary and analysis process. The CWD data often are grouped into categories of interest, such as decay class, species group, or diameter class, to facilitate comparisons among, for example, habitat types within geographic areas. Before an analysis is conducted on these categories, however, the individual piece estimates either must be summed within groups to the

plot level or, if multiple conditions exist on a plot, to the condition class level.

3.4. Biomass

Biomass estimation involves the cubic volume of a log, density of water (62.4 lb/ft^3), specific gravity of solid wood (Forest Products Laboratory, 1987, Table 4-2), and a reduction factor dependent on the decay class. The equations presented in Table 3 estimate the oven-dry weight of a down log. Specific gravity decreases as a log decays, which reduces the weight of a log as it decomposes from decay class 1 to class 5 (Harmon and Sexton, 1996). To account for this, a decay class reduction factor (DCR) was developed to adjust the weight of a log by successively lowering the specific gravity of decay classes 2, 3,

Table 3

Equations to estimate biomass per-unit-area (oven-dry weight) of individual CWD pieces tallied with the line-intersect sampling method on resource inventory plots

Attribute	Equation[a]
Tons per acre	(Cubic feet per acre) $\times$ (62.4 lb/ft^3/2000 lb/t) $\times$ SpG $\times$ DCR
Kilograms per hectare	(Cubic meters per hectare) $\times$ 1000 kg/m^3 $\times$ SpG $\times$ DCR

[a] Cubic feet per acre and cubic meters per hectare are calculated for each piece with equations from Table 2. SpG: the specific gravity of fresh wood, varies by species (Forest Products Laboratory, 1987, Table 4-2). DCR: decay class reduction factor; reduces the specific gravity for decaying wood (see Table 4).

Table 4
Decay class reduction factors for coarse woody debris, by decay class and species group

Decay class	Species group	
	Softwoods	Hardwoods
1	1.00	1.00
2	0.84	0.78
3	0.71	0.45
4	0.45	0.42

and 4 (Table 4). An average DCR was estimated for softwoods based on data presented in Harmon and Sexton (1996) and for hardwoods based on personal communication with Harmon (1999). Biomass (weight) estimation often is calculated by using only the specific gravity of solid, green wood for all stages of decay. The addition of a decay-related reduction factor, as described above, to the biomass equations improves the biomass estimate and more accurately reflects the weight of decomposing down wood collected in extensive resource inventories.

Biomass estimates can be used for a number of purposes, such as assessing the contribution of down wood to the total fuel loading (i.e. tons per acre) on a site, or as the basis for conversion to the amount of carbon tied up in the CWD component of an ecosystem. Birdsey (1992) describes how carbon can be estimated from wood biomass by using an average conversion factor of 0.521 for softwoods and 0.491 for hardwoods. An estimate of the amount of carbon stored in down wood can be calculated by applying one of these factors to a CWD biomass estimate as follows:

weight of carbon per-unit-area

$$= \text{biomass per-unit-area} \times (0.521 \text{ or } 0.491) \quad (4)$$

4. Analysis of CWD attributes

The plot-level per-unit-area sum is either expanded by the area (acres or hectares) associated with the inventory plot or averaged across plots to produce a mean per-unit-area value for the attribute. Mean per-acre or per-hectare values are a common way to present CWD estimates because they allow for easy comparison among different forest types, habitats, or geographic locations. For example, the average

volume per acre of down wood might be analyzed for trends along moisture or elevational gradients in western Washington. Or, the mean density of CWD (i.e. logs per acre) might be compared among habitats or disturbance levels. When calculating means, it is important to use all plots sampled in an inventory, including those that had no tally or had attribute values equal to zero on the plot.

Population estimates also can be estimated by multiplying the plot expansion factor (i.e. hectares) by the plot-level per-unit-area estimate. For example, the total amount of carbon stored in large-diameter (>50 cm) softwood logs in western Oregon can be calculated by following a number of simple steps:

1. estimate the biomass per hectare for each individual log;
2. convert biomass per hectare to carbon per hectare by multiplying by 0.521;
3. sort the logs on each plot by diameter class, and sum the carbon per hectare for logs >50 cm in diameter tallied for the plot or condition;
4. expand this plot-level (or condition level) carbon per hectare sum by the hectares associated with the plot (or condition), resulting in the weight of carbon on the plot (i.e. kilograms or tons);
5. sum the estimate of carbon across all plots in western Oregon.

Another type of analysis might focus on the individual attributes of CWD logs tallied in the inventory. Characteristics of the actual log resource, such as the longest piece length, the average large-end diameter, or the species having the greatest log volume, may provide additional information and insights about the CWD population.

One of the most useful features of integrating CWD transects with permanent resource inventory plots is the ability to relate CWD data with all stand or tree level information available for the inventory plot, such as current or past tree mortality, snag density, stand age, or disturbance history. This connection of CWD data to the surrounding forests provides a valuable source of information for many ecological studies.

4.1. Example of CWD calculations

Table 5 displays several measurements collected on two forest inventory field plots. The equations in

Table 5
CWD measurements and estimates for two sample inventory plots

Plot	Subplot	Transect ID	Decay class	Diameter small-end (cm)	Diameter large-end (cm)	Log length (m)	Log volume (m³)	Cubic volume per ha (m³/ha)	Density (logs per ha)	Percent cover
100	1	N	1	15	50	12	1.3	9.3	7	0.28
	1	SE	3	25	60	15	2.5	14.5	6	0.37
	1	SW	4	20	55	20	2.7	11.7	4	0.33
	2	N	4	40	100	40	18.2	39.8	2	0.61
	2	NE[a]	0	0	0	0	0	0	0	0.0
	2	SW	4	50	75	15	4.8	27.8	6	0.55
	3	N	2	33	88	25	8.7	30.3	3	0.53
	3	N	3	20	30	5	.39	4.5	17	0.22
	3	SE	1	21	29	7	.35	4.4	12	0.22
	3	SW	4	54	61	3	.78	22.7	29	0.50
200	1	N	2	12.5	13	2	.03	1.1	44	0.11
	1	SE	1	85	110	3	2.28	66.2	29	0.85
	1	SW	1	14	77	10	2.4	21.0	9	0.40
	2	N	2	38	76	22	6.2	24.7	4	0.50
	2	SE	4	82	129	5	4.6	80.1	17	0.92
	2[b]	SW	1	90	120	12	10.6	77.1	7	0.92
	2	SW	3	25	80	10	2.8	24.1	9	0.46
	3	N	1	14	20	3	.07	2.0	29	0.15
	3	SE	3	12.5	40	6	.41	6.0	15	0.23
	3	SW	3	45	70	5	1.36	23.7	17	0.50

[a] The NE transect on plot 100, subplot 2, has no tally.
[b] Plot 200, subplot 2, has two pieces of down wood tallied on the SW transect.

Table 2 were used to calculate volume per hectare, logs per hectare, and percentage of cover. Individual log volume was estimated with Smalian's formula. In this example, each plot has three subplots with three transects that run north (N), southeast (SE), and southwest (SW). The length of each individual transect is 20 m, for a total transect length (L) of 180 m on the plot. Each line in Table 5 represents one piece of CWD tallied along the transect.

To estimate the mean volume per hectare, calculate the total volume per hectare for each plot by first summing the volume per hectare of all individual pieces tallied on the plot. Calculate the mean of the CWD attribute from the two plots (i.e. $(165 + 326)/2 = 245.6$). In this inventory, there is mean volume of 245.6 m³/ha. The mean density of CWD is 134 logs per hectare with a mean percentage of cover of 4.3% across the inventory area. A comparison of CWD attributes among decay classes requires that data be summed within each decay class on each plot before calculating the mean across plots (Table 6). In this example, there is a mean of about 90 m³/ha of CWD

Table 6
Total and mean volume per hectare within decay classes on each plot

	Decay classes			
	1	2	3	4
Plot 100	13.7	30.3	18.9	102.1
Plot 200	166.4	25.9	53.8	80.1
Mean	90	28	36	91

found in decay classes 1 and 4, compared to a mean of only 28 m³/ha in decay class 2.

5. Conclusion

This paper described an application of LIS developed for FIA resource inventories to sample CWD in western US forests. Several existing techniques and methods were combined to produce the framework for the application. Sampling and estimation procedures were modified to work with the FIA plot layout

and inventory design, and a measurement protocol was developed specifically to allow field crews to collect data with consistent and repeatable methods. Equations are presented to estimate volume, biomass, carbon, percentage of cover, linear feet, and density of CWD logs tallied on transects in a resource inventory.

Many characteristics of CWD are of interest to wildlife biologists, ecologists, fuels specialists, and other resource managers. Line-intersect sampling combined with DeVries' (1973) estimation equations enables an inventory program to respond to an evolving set of resource questions and information needs regarding CWD; for example, new or additional measurements can be recorded for CWD logs, thereby allowing the calculation of new attributes, important for new lines of research.

Another group interested in CWD are those studying criteria and indicators (C&I) defined for the conservation and sustainable management of boreal and temperate forests in the Montreal process (USDA Forest Service, 1997) and the Santiago declaration (Anonymous, 1995), which require an analysis of the contribution of forest ecosystems to the global carbon cycle (criterion no. 5). The specific indicators examine how the total forest biomass and carbon pool differ by forest type, age class, and successional stages. The intent is to evaluate the absorption and release of carbon in forest ecosystems by analyzing the standing live and dead biomass, CWD, peat, and soil carbon. To accomplish the goals of these comprehensive international agreements it is important to frame resource assessments in terms of the specific indicators to facilitate regional and international comparisons of C&I data for policy evaluation.

Unlike some studies that have focused on one watershed or geographic location, the addition of CWD measurements to forest inventory field plots across Oregon, Washington, and California will allow FIA to estimate the extent, distribution, and characteristics of the CWD population across millions of hectares of land.

Acknowledgements

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